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The effect of joystick handle size and gain at two levels of required precision on performance and physical load on crane operators

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The study was designed to determine the effect of joystick handle size and (display-control) gain at two levels of required task precision on performance and physical load on crane operators. Eight experienced crane operators performed a simulated crane operation task on a computer by use of a joystick with either a short or a large handle. The task was performed at three gain levels and at two levels of required precision. Task performance, wrist and forearm postures, upper extremity muscle activity, perceived exertion and perceived comfort were measured.

Task performance improved when using the joystick with the short handle and when working at a higher gain, while physical load decreased or remained the same. An increased level of required task precision was associated with a lower performance, but physical load was not affected. External validity of the simulated crane task seemed sufficient enough to extrapolate the results to practice.

A joystick with a short handle is recommended, as this leads to an increased performance whilst the operator's physical load decreases or remains the same. Further optimization of performance and physical load can be achieved by optimizing gain settings of the joystick in relation to the task and type of joystick used.

Keywords: Joystick operation; Gain; Precision; Performance; Kinematics; Electromyography

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1. Introduction

Over the last 40 years an extensive mechanization and rationalization took place in the forest, mining and construction industries, which led to a large increase in productivity. Meanwhile, the physical characteristics of the tasks of the workers changed drastically, from physically strenuous work to long periods of low-intensive joystick operation (Attebrant *et al.* 1997). This joystick operation in machines is characterized by long periods of sitting in fixed, non-neutral body postures, while the hands are moving the controls in repetitive short-cycle movement patterns. In forestry, these activities may take up to 90–95% of the total working time (Hansson 1990), while the number of wrist movements can be even more than 20 000 per shift (Golsse 1989). Moreover, joystick operation often requires a high level of precision with only little room for errors.

The exposure to repetitive upper extremity motion patterns, long work periods, non-neutral body postures and high precision demands are known risk factors for upper extremity complaints (Milerad and Ericson 1994, Punnett and Wegman 2004). Furthermore, the risk of complaints is even more pronounced when a job includes a combination of two or more of these risk factors (Punnett and Wegman 2004). Therefore, it is not surprising that the incidence of complaints of the upper extremity and neck is high among operators. In a cross-sectional study of 1174 forestry machine operators, Axelsson and Pontén (1990) found that 50% of the operators reported an 'overload syndrome', mainly characterized by shoulder and neck complaints. About 90% of the operators associated their complaints with the one-sided static work, the controls and the seat (Axelsson and Pontén 1990).

With this high prevalence of musculoskeletal complaints in operators there is a need for ergonomic optimization of joystick control in terms of reducing workload and maintaining or improving performance. One of the aspects in joystick operation that can be optimized is the joystick handle. The handheld joystick, which has a relatively large handle and is mainly operated with the whole arm and the hand, is most commonly used in heavy machines. Several years ago the mini joystick was introduced in the forest industry, which, as a result of the short handle, is mainly operated by the fingers in the palm of the hand. Results from earlier studies indicated that the use of a mini joystick may be beneficial, from the perspectives of both health and the performance of the operator. Asikainen and Harstela (1993) and Attebrant *et al.* (1997) found lower muscle activity in the trapezius muscle when the mini joystick was compared with the conventional handheld joystick. The mini joystick also seemed to have a positive effect on performance. Time to complete the task was reduced in the study of Attebrant *et al.* (1997) when a mini joystick was used on a forest machine. In the study of Asikainen and Harstela (1993), not the time of task completion but the quality of task performance was improved when the mini joystick was used. This increased performance was explained by saying that 'the hand and the fingers, with the small muscles of the distal joints, are especially suitable for executing short, fast and precise movements typical of the mini joysticks'. Despite the apparent positive effects of the use of mini joysticks in precision tasks, the application of mini joysticks in industries other than the forest industry, such as the construction industry, is still limited.

Another aspect that can be optimized in joystick operation is display-control gain. In machines operated by joysticks, a change in position of the joystick often results in a change of speed in the element of the machine that is operated. Display-control gain is defined as the output of the machine element (speed) given a certain input of the joystick (position as defined by deflection). With a low gain, a certain deflection of the joystick results in a low speed of the element of the operated machine. With a high gain the same deflection of the joystick will result in a higher speed. The optimal gain can be found by balancing the advantages of a relatively high gain (i.e. reduction of the time to reach target) against the advantages of a relatively low gain (i.e. reduction of final corrective movements when close to target) (Buck 1980). In the literature, little is known about the effect of gain on health-related parameters. The effect of gain on performance has mainly been measured in computer tasks. A U-shaped relationship has been found between gain and movement time, where the minimum movement time represented the optimum gain (Lin *et al.* 1992).

In the present study the aim was to determine the effect of joystick handle size (short vs. large handle) and (display-control) gain at two levels of required task precision on performance, wrist and forearm posture, upper extremity muscle activity, perceived exertion and perceived comfort in operators performing a simulated crane operation task.

2. Methods

2.1. *Subjects*

Eight healthy male crane operators participated in the study (mean age 50 (SD 7) years, mean stature 1.85 (SD 0.08) m and mean body weight 98 (SD 17) kg). Prior to the experiment, the subjects completed an informed consent form. All subjects were right-hand dominant and none reported complaints in the back, neck, shoulders or arms within the previous year. The operators had on average 26 (SD 8) years of experience in working with machines operated by levers or handheld joysticks. None of the operators had experience in working with joysticks with short handles. The study was approved by the Faculty's Ethical Committee.

2.2. *General procedure*

The subjects were seated in a crane control unit, consisting of a chair with armrests and a joystick on the right-hand side, in front of a computer screen. Seat height, fore–aft position of the chair, height of the armrest, fore–aft position of the armrest and height of the joystick were also adjusted to the anthropometry of each subject, to ensure that subjects sat with knees at 90°, feet flat on the ground, lower arms horizontally on the armrests and upper arms vertical with relaxed shoulders (elbow angle 90 degrees). The top of the computer screen was placed at eye height in order to keep the neck in a neutral position. Both forearms were neutral with regard to pronation and supination and to ulnar and radial deviation at the wrists. The height of the joystick and fore–aft position of the subject were adjusted in such a way that the subject (in the posture described above) could hold the joystick with the right hand in the middle of the handle (as seen in figure 1).

First, reference measurements for kinematics were performed. Position of the markers, placed at the hand, forearm and upper arm, were recorded in a standard reference posture, defined as the neutral posture in which the subject was sitting erect, keeping the upper arm vertical, the elbow in 90° flexion and the forearm horizontal, and neutral with regard to pronation and supination (i.e. with thumb pointing upward) and with regard to ulnar-radial deviation and palmar-dorsal flexion at the wrist. In the same reference posture, the subject's ranges of motion (ROM) for pronation and supination in the forearm, palmar and dorsal flexion in the wrist and ulnar and radial deviation in the wrist were measured (with movement directions as described in Kee and Karwowski 2001).

Figure 1. Experimental arrangement; the subject was seated in a crane control unit in front of a computer screen supplied with a joystick on the right hand side.

The subject was asked to move from the reference posture towards the maximum joint angle in the prescribed direction and to maintain this maximum joint angle for 4 s. The ROM for each of the six directions was measured twice.

A joystick control system (Sakae type S50JCK-Y0–25R2G; maximum deflection 30° in each direction, actuating force 7 N; Sakae Tsushin Kogyo Co. Ltd., Kawasaki, Japan) was supplied with a short handle (length 70 mm, diameter 30 mm) and with a large handle (length 140 mm, diameter 40 mm) (figure 2).

The joystick was used to perform a simulated crane operation task on a computer screen (programmed in LabVIEW; National Instruments Corporation, Austin, TX, USA). A mobile crane was shown in side view with a load attached to the hook of the winch (figure 3). In front of the crane two containers were shown with an obstacle in between. By moving the joystick, the crane could be operated, which resulted in a movement of the load across the screen. Operation of the simulated crane was in accordance with the basic control arrangement and directions of movement of controls in mobile cranes as given in the ISO 7752 part 2 (International Organization for Standardization 1986). Moving the joystick to the left caused the boom of the crane to move upward and moving the joystick to the right resulted in moving the boom downward. Moving the joystick forward caused the winch to lower the load, while a backward movement of the joystick resulted in the winch raising the load. Motions in the two axes could be operated simultaneously.

Subjects were instructed to move the load, by operating the boom and the winch of the crane, as often as possible from the left container into the right container and back again within 1 min. The subjects were specifically instructed to avoid errors, such as bumping the load into the side or the bottom of the container or bumping into the obstacle. When an error was made, the subject was notified by a beep. No further feedback on performance (i.e. number of times the load was put into a container or the number of errors) was given.

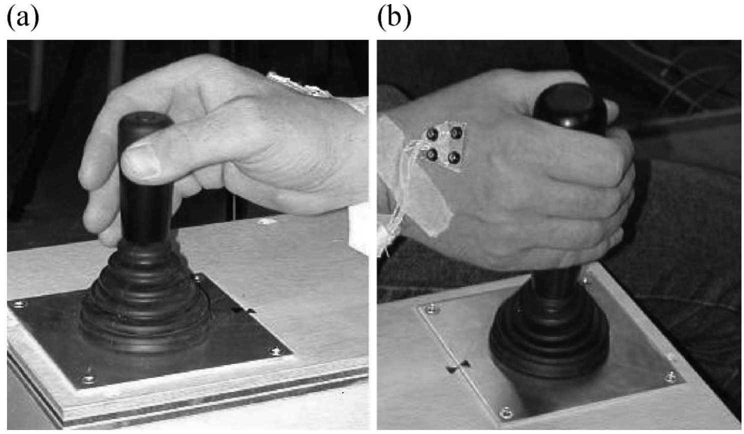

Figure 2. Joystick controls: joystick with the short handle (a) and joystick with the large handle (b).

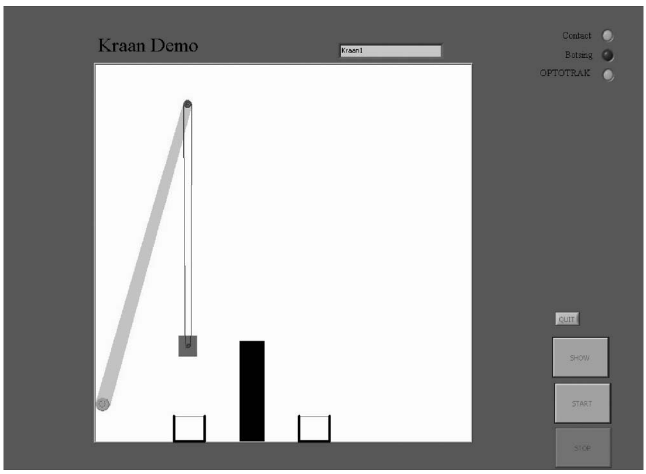

Figure 3. Computer simulation of the crane task. In a side-view a mobile crane was shown with a load attached to the hook of the winch. In front of the crane two containers were shown with an obstacle in between.

To become acquainted with the task, the subjects performed ten 1-min practice trials. A pilot study showed that these ten practice trials were required to obtain a stable performance at the task.

All subjects performed the task using both the joystick with the short handle and the one with the large handle. In addition, three (linear) display-control gains were tested: a low, middle and high gain. Each of the tested gains consisted of a combination of a gain for the boom and a gain for the winch. From a pilot study three gain combinations were selected that operators felt were realistic. Finally, subjects performed the task with two levels of required task precision determined by the size of the container; in the high precision condition the size of the container was 4/3 (12 mm $\times$ 12 mm) the size of the load, while in the low precision condition the container was 5/3 (15 mm $\times$ 15 mm) the size of the load. Four operators started with the joystick with the short handle, while the other four started with the large handle. With each joystick the six experimental conditions (a combination of three levels of gain and two levels of required precision) were assigned in a randomized order. Each condition was performed twice.

2.3. *Measurement and data analysis*

2.3.1. Performance measures. Displacement of the joystick resulted in a change of voltage in the built-in potentiometers. The output voltage was registered by the computer and resulted in a corresponding angular velocity of the boom or velocity of the winch cable on the screen. The angle of the boom and the length of the winch cable determined the position of the load on the screen. The x- and y-coordinates of the centre of the load were recorded by the computer with a sampling frequency of 50 Hz. Two performance measures were calculated for each experimental trial of 1 min: 1) number of repetitions; 2) number of errors. The number of repetitions was expressed as the number of times that the load was moved from one container to the other, plus the fraction of the final trajectory that was covered before the end of the trial. The numbers of errors were recorded.

2.3.2. Physical measures.

2.3.2.1. Kinematics. Small plastic plates, each with four LED markers, were attached to the following body segments at the subject's right hand side: upper arm (on the lateral side, just proximal of the lateral epicondyle); forearm (on the dorsal side, just proximal of the styloid processes); and hand (on the dorsal side, just proximal of the second and third head of the metacarpal bone) (as shown in figure 1). These specific locations were selected to ensure that the movement between each plate and the segment during movement of the upper extremity would be minimal. The 3D marker positions were recorded using an opto-electronic system (Optotrak; Northern Digital Inc., Waterloo, Ontario, Canada) with one camera unit (containing three cameras) sampling at 50 Hz. For each segment three visible markers were used to calculate the joint angles.

3D kinematics were measured to calculate the angle of the hand with regard to the forearm and the angle of the forearm with regard to the upper arm during the experimental trials and during the ROM measurements, all expressed relative to the angles in the neutral standardized reference posture, aligned with the global axes system. To calculate the angles, a local coordinate system was determined for each segment (upper arm, forearm and hand) in the standardized reference posture, using the surface drawn through the three markers for each segment (hand, forearm and upper arm). Then, for all experimental trials and ROM measurements, the same local coordinate system was determined at each moment in time. Subsequently, the coordinate system in the reference posture was used to calculate the orientation of the anatomical axes of each segment at each instant of time. Next, both elbow and wrist angles were determined by calculating the orientation of the coordinate system of the distal segment (i.e. forearm for elbow angles and hand for wrist angles) in the coordinate system of the proximal segment (i.e. upper arm for elbow angles and forearm for wrist angles). Finally, Euler angles were calculated for both the elbow joint and the wrist joint by decomposing the rotation in the following order:

- elbow joint: flexion-extension, pronation and supination and abduction and adduction (the pronation and supination angles were used in the analysis);

- wrist joint: palmar and dorsal flexion, ulnar and radial deviation and rotation (the former two rotations were used in the analysis).

The ROM for each joint angle (forearm pronation and supination, wrist palmar and dorsal flexion and wrist ulnar and radial deviation) was determined by finding the maximum value for a running average window of 1 s of the two attempts in each extreme joint position. The time series recorded for angles at wrist and elbow during the experimental trials were normalized to the individual ROM in the corresponding movement direction. Median joint angles were determined for each condition. Furthermore, normalized time series were divided into the percentage of time spent in joint angles of 50–100% ROM and the percentage of time spent in joint angles of 75–100% of ROM during the task. Wrist and forearm angles of 0–50% ROM are considered to be acceptable joint postures; joint postures larger than 50% ROM are considered to be undesirable and if these postures have to be adopted for a long period of time, ergonomic interventions are recommended. Moreover, joint postures between 75–100% ROM are considered to be extreme joint postures, which should be avoided at all times.

2.3.2.2. Muscle activity. The electromyographic (EMG) signals of six muscles at the subjects' right side were recorded:

- in the neck-shoulder: M (Musculus) trapezius pars descendens (TRR);
- in the upper arm: M. biceps brachii (BB) and M. triceps brachii lateral caput (TBL);
- in the forearm: M. extensor carpi radialis (ECR), M. extensor carpi ulnaris (ECU) and M. flexor carpi radialis (FCR).

Bipolar Ag/AgCl (Blue Sensor) surface electrodes, with a gel-skin contact area of 1 cm^2, were positioned according to Franssen (1995) with an inter-electrode distance of 25 mm. A reference electrode was placed on the seventh spinous process. EMG signals were amplified 20 times (Porti-17^{TM}, TMS, Enschede, The Netherlands; input impedance $> 10^{12}\ \Omega$, Common Mode Rejection Ratio (CMRR) $>$ 90 dB), band-pass filtered (10–400 Hz) and A-D converted (22-bits) at a sample frequency of 1000 Hz. EMG signals were full-wave rectified and low pass filtered at 10 Hz (fourth order Butterworth filter) using MATLAB (The MathWorks, Inc., Natick, MA, USA)(Clancy *et al.* 2002). The mean activity level was calculated.

2.3.3. Subjective measures.

2.3.3.1. Perceived exertion. After the second attempt of each experimental condition, the rating of perceived exertion in the upper body (neck, shoulders, elbows, hands) was measured using a 10-point Borg scale (Borg 1982).

2.3.3.2. Perceived comfort. After finishing all experimental trials with one joystick, the crane operators were asked to rate their perceived comfort of that particular joystick on a 7-point scale with '1' indicating that the joystick was 'very uncomfortable' and '7' that the joystick was 'very comfortable' (Kuijt-Evers *et al.* 2005).

2.4. *Statistical analysis*

Repeated-measures ANOVA were used to determine the main effects of joystick (two levels), gain (three levels), precision (two levels) and attempt (two levels) on number of repetitions, number of errors, normalized pronation and supination, normalized ulnar and radial deviation, normalized palmar and dorsal flexion and muscle activity. The effects of joystick handle (two levels), gain (three levels) and precision (two levels) on perceived exertion were also evaluated using an ANOVA for repeated measures. One-way ANOVA and paired t-tests with Bonferroni corrections were used for post-hoc testing. The effect of joystick handle on perceived comfort was tested by a paired t-test. A p-value less than 0.05 was considered to be statistically significant.

3. Results

A main effect of attempt (first vs. second attempt) was not found. This indicates that the performance on the task was consistent and that a learning effect was not present. Therefore, the independent variable 'attempt' is not reported in the results below.

3.1. *Performance measures*

3.1.1. Number of repetitions. Main effects were found for joystick handle size ($p = 0.017$), (display-control) gain ($p < 0.001$) and precision ($p = 0.001$) on the number of repetitions. The use of the short handle led to significantly more repetitions compared with the large handle. At the lowest gain, significantly fewer repetitions were established compared with the higher gains (middle gain and high gain). Finally, in the high precision condition, the number of repetitions was significantly lower compared with the low precision condition (figure 4). In addition, two significant interaction effects on number of repetitions were found, namely, joystick handle size*precision ($p = 0.027$) and gain*precision ($p = 0.017$), which indicated that at higher precision demands the differences between handles and gains became smaller.

3.1.2. Number of errors. The number of errors was only affected by the precision demands of the task ($p = 0.009$). In the high precision condition, significantly more errors

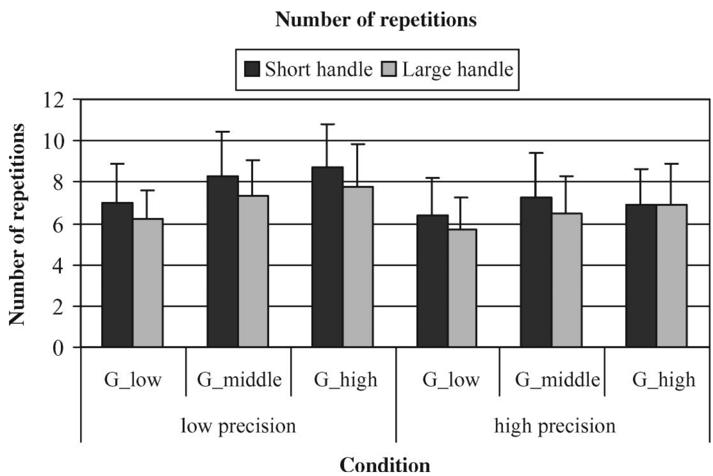

Figure 4. Mean and standard deviation (error bars) of the number of repetitions for the joystick with the short handle and the large handle, at the three gain levels (G_low, G_middle, G_high) and at low and high precision.

were made compared with the low precision condition (figure 5). No other main or interaction effect on the number of errors was found.

3.2. *Physical measures*

3.2.1. Joint kinematics. Large inter-individual differences were found for the median posture in which the joystick was operated. Figure 6 shows the median posture in palmar and dorsal flexion and in ulnar and radial deviation for all subjects in all conditions for the joystick with the short handle and for the one with the large

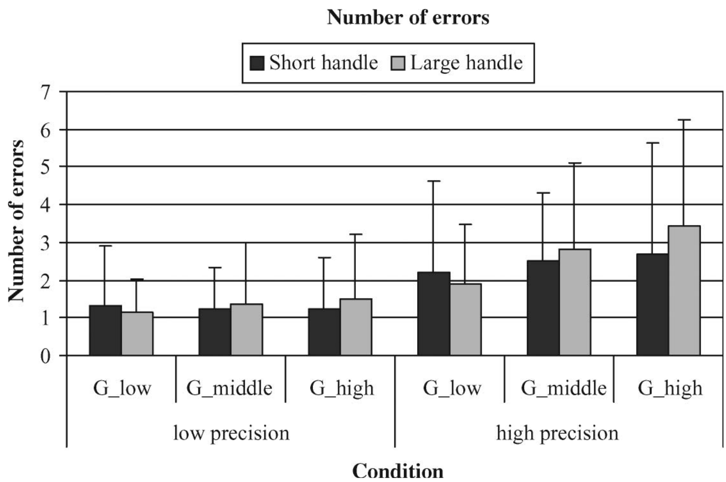

Figure 5. Mean and standard deviation (error bars) of the number of errors for the joystick with the short handle and the large handle, at the three gain levels (G_low, G_middle, G_high) and at low and high precision.

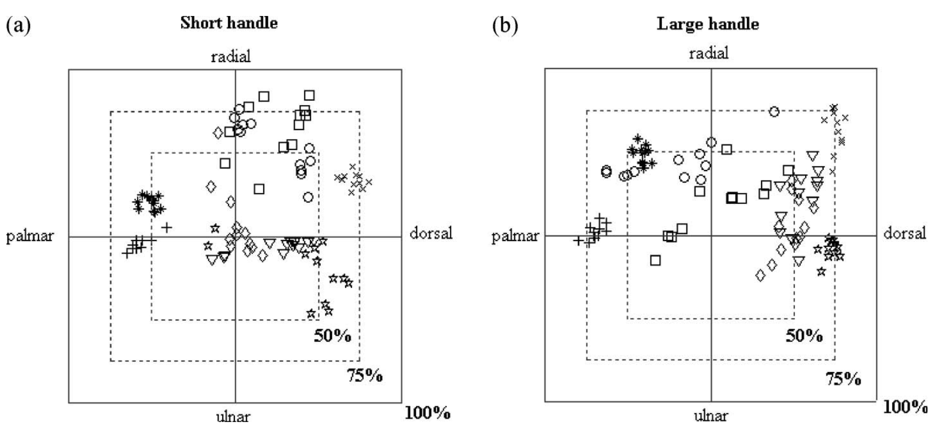

Figure 6. Median wrist posture in which the joystick was operated. (a), values for the joystick with the short handle. (b), values for the joystick with the large handle. Each symbol represents a subject, for whom all conditions are presented.

handle. Table 1 shows the mean and standard deviation of the absolute ROM in each movement direction.

The percentage of time above 50% ROM in pronation and supination, ulnar-radial deviation and palmar-dorsal flexion was not significantly affected by joystick handle size, gain or precision. However, the percentage of time in palmar and dorsal flexion above 75% ROM was significantly affected by handle size ($p = 0.029$) and gain ($p = 0.013$). With the joystick with the large handle, a significantly higher percentage of time was spent in extreme palmar and dorsal flexion (figure 7). A Bonferroni post-hoc test revealed that at the lowest gain more time was spent in extreme palmar and dorsal flexion compared with the highest gain. No effect of joystick handle size, gain or precision was found on percentage of time in extreme (>75% ROM) ulnar-radial deviation or pronation and supination. In fact, no time at all was spent in extreme (>75% ROM) pronation and supination. Interaction effects were not observed for extreme forearm or wrist postures.

3.2.2. Upper extremity muscle activity. The mean muscle activities of the TRR, BB, TBL, ECR, ECU and FCR were not significantly affected by joystick handle size, gain or precision. Only for the ECU muscle a significant interaction was found for joystick and

Table 1. The mean and standard deviation of the absolute range of motion values as measured in the standardized reference posture.

	Wrist joint angles (°)				Elbow joint angles (°)	
	Palmar flexion	Dorsal flexion	Ulnar deviation	Radial deviation	Pronation	Supination
Mean	63.86	38.23	22.27	14.78	57.51	67.59
SD	7.47	8.73	3.49	2.24	8.58	9.45

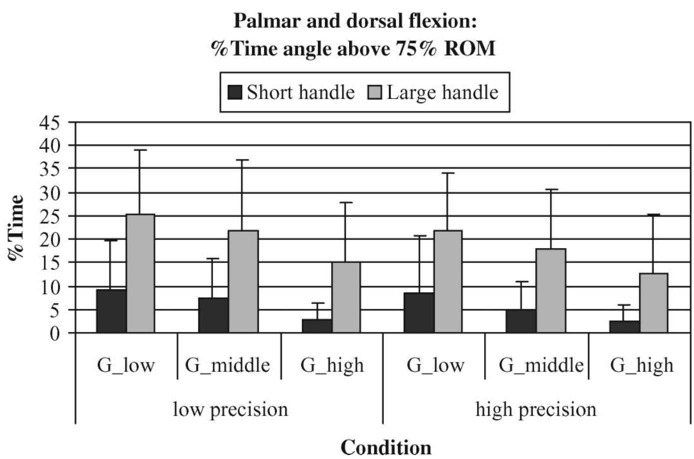

Figure 7. Mean and standard deviation (error bars) of the percentage of time spent in palmar and dorsal flexion above 75% range of motion (ROM) for the joystick with the short handle and the large handle, at the three gain levels (G_low, G_middle, G_high) and at low and high precision.

precision ($p = 0.028$). The difference in ECU activity between the short and the large handle was larger at lower precision demands, with the joystick with the large handle demanding a higher ECU activity.

3.3. *Subjective measures*

3.3.1. Perceived exertion on task. Joystick handle size and gain did not affect perceived exertion. However, perceived exertion was significantly affected by precision ($p = 0.008$) (low precision: mean exertion 2.6 (SD 0.2); high precision: mean exertion 3.6 (SD 0.4)). With high precision demands, the task was considered to be more demanding as compared with low precision demands.

3.3.2. Perceived comfort of joysticks. There was no significant effect of joystick handle size on perceived comfort (short handle: mean comfort 5.1 (SD 1.2); large handle: mean comfort 4.9 (SD 1.1)). Four participants gave higher comfort ratings to the short handle, two participants rated comfort of the large handle higher and two participants gave similar ratings to both joystick handles.

4. Discussion

The present study was designed to compare the use of joysticks with a large and a short handle at three levels of display-control gain and at two levels of required task precision with regard to performance, wrist and forearm posture, muscle activity, perceived exertion and perceived comfort. The results showed that performance improved when using the short handle and when working at a higher gain, while physical load decreased or remained the same. An increased level of task precision was associated with lower performance, but physical load was not affected.

All crane operators showed a higher productivity when using the joystick with the short handle. This is likely a result of the smaller ROM associated with moving the short handle, thus making the overall time to cover the movement span shorter and, therefore, increasing productivity (number of repetitions). It is remarkable that, even though none of the operators had ever worked with joysticks with short handles, they were immediately more productive when using this handle. A higher productivity with a short handle was also found in a field study by Attebrant *et al.* (1997). In one of three tasks tested, task duration was reduced when working with a short handle. For the other two tasks they found no effect of type of handle on performance. This result may be explained by the shorter task duration of these two tasks, which may have been too short to find an effect, or by the fact that quality of task performance may have been different for the two different handles. The latter was observed in a study by Asikainen and Harstela (1993), who found that with a short handle task duration remained the same but the accuracy of task performance increased. However, quality of task performance was not reported by Attebrant *et al.* (1997). In the present study the accuracy was kept at a relatively constant level by instructing the participants to avoid errors, such as bumping the load into the side or the bottom of the container or bumping into the obstacle, while at the same time striving for as many repetitions as possible. Effects of handle size and gain did not lead to differences in the number of errors and, therefore, the main productivity measure was reflected in the number of repetitions.

The differences in the ways the two joystick handles are operated can explain why a significantly longer time was spent in extreme wrist postures when the large handle was used. Because of the larger movement span, relatively large movements of the arm are required to control the large handle. In addition, because the joystick is held with the whole hand, the hand has to follow the required deflection of the joystick, for which relatively large wrist angles are needed. The joystick with the short handle requires less arm and wrist movements because of the shorter movement span and because the joystick is not continuously held with the whole hand, but mainly manipulated with the fingers. However, during joystick operation with the short handle, wrist postures were not neutral continuously. When the joystick was moved near the margins of its movement span, larger wrist angles and movement of the arm were observed, probably caused by the combination of the deflection angle and the length of the handle. Further optimization of both joystick handle length and maximum deflection angle is recommended to achieve joystick operation with relatively neutral wrist postures and minimal arm movements. This would make it possible to use the armrests effectively and to unload the neck-shoulder muscles.

No effect of joystick handle size on muscle activity was found and, since the data showed no systematic trend, it is expected that differences would remain absent when a larger population would have been tested. This is in disagreement with the findings of Attebrant *et al.* (1997), who found that muscle activity increased when a conventional, large handle was used, as compared with a short handle. One of the reasons that no effect was found may be that the stiffness of the joysticks was kept constant in the present study. In the study of Attebrant *et al.* (1997), the stiffness of the conventional joystick was higher than the stiffness of the joystick with the small handle, resulting in a decrease in muscle activity when operating the joystick with the small handle. Also Lindbeck (1985) reported higher muscle load associated with higher lever resistance. Another reason for finding no effect of joystick handle on muscle activity may be that there was not enough contrast in the ways that the short and the large handle were operated. The differences between the two joysticks tested in the study of Attebrant seemed to be greater. Operation of their mini joystick did not necessitate movement of the arm (since their handle was shorter), whereas their conventional joystick required movement of the entire arm. Moreover, their conventional joystick was operated with the hand on top of the joystick and with the forearm pronated, whereas their mini joystick was operated with the forearm in a neutral position with regard to pronation and supination. It may also be that the expected effect of handle size on muscle activity was undone by the higher working speed observed when handling the short handle, which resulted in an increased productivity.

In the present study, muscle activity was also not affected by precision demands in the task, whereas some studies have shown that, as a result of higher precision demands, muscle activity increased (Milerad and Ericson 1994, Laursen *et al.* 1998, Visser *et al.* 2004). However, it has also been reported that, with higher precision demands, muscle activity can remain unchanged or even decrease, if the higher precision is compensated with a lower working speed (Birch *et al.* 2000a,b, Visser *et al.* 2004), as was the case in the present study.

For the joystick with the large handle in the simulated crane operation task in this study, the optimal gain was probably not reached, as performance still improved at the highest gain. Although not statistically significant, for the joystick with the short handle the middle gain in the high precision condition tended to be the optimal gain (figure 4). Different optimal gains for the joysticks with the short and large handle are to be expected because, for the same deflection angle of both handles, the movement span in which precision needs to be regulated is smaller for the short handle (figure 8). When the

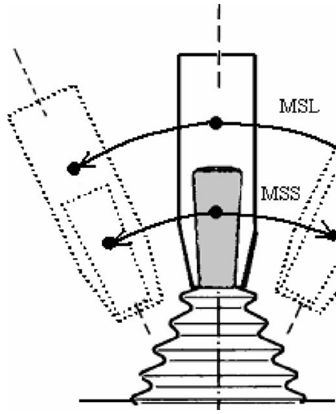

Figure 8. Movement span of the large handle (MSL) is larger than the movement span of the short handle (MSH) while the maximum deflection angle of the joystick is the same.

same movement span is covered by both handles, the deflection angle of the short handle is larger and thus a higher speed is generated (as is a higher gain). This would imply that the optimal gain to work precisely is lower for the short handle.

Optimal gain may not only be affected by joystick characteristics, such as handle size, but also by task characteristics. In the present study the simulated crane operation tasks consisted of two phases: 1) a movement phase with low precision demands; 2) a positioning phase in which precision was varied (high and low). Although it is expected that including the two phases in the simulated crane operation task increases generalization, in practice the ratio between the two phases will not be equal to the ratio in the simulation and the ratio will vary considerably across tasks. A relatively high gain (small joystick movement, high speed) will be favourable for tasks with a relatively large movement phase, and a relatively low gain (large joystick movement, slow speed) will be favourable for tasks with a relatively large positioning phase. Therefore, determining the optimal gain for machine operations involving joystick control may be difficult and task specific. It may be advisable to design joystick control such that gain settings of the machine can be changed depending on the type of task that is performed.

Experienced crane operators had to perform a crane operation task simulated on a computer screen. It may be questionable whether the simulation was representative for real-life crane tasks. First, the sling of the winch was not programmed in the task, which excluded the effect of inertia of the load and external influences on the load, such as wind. Second, visual feedback of the task was given from a side view, whereas normally the task is viewed from behind (from the cabin). Finally, no whole body vibrations were present during performance of the simulated crane operation task, as opposed to the shocks and vibrations normally present in the crane cabin due to, for example, vibrations of the motor system, driving or working on uneven ground or to movements of the load. However, simulating the crane operation task allowed for a high level of standardization and, thus, results are minimally biased by external influences. Moreover, experienced crane operators participated in the study. They were accustomed to the task they performed, to the way the joystick had to be controlled and to operating the joystick with the large handle. Because they were not used to working with a short handle, the task was practised with this handle until a stable performance was reached. The crane operators emphasized that, in spite of the simplifications in the task, the crane task and crane control unit felt realistic. It may, therefore, be concluded that the results of the present study may be applicable to machines that are used for tasks similar to those tested in this study, i.e. mobile cranes, tower cranes and harbour cranes.

The results of the present study indicate that the joystick with the short handle is advisable for application in practice. The short handle may contribute to an increase in productivity and a more desirable physical load for the operator. Also, the potential for increased productivity may increase the opportunity to take micro breaks, which have been shown to have a positive effect in reducing discomfort (McLean *et al*. 2001). Further optimization of the joystick with the short handle is advisable because, in some cases, maximum deflection of the joystick was still associated with extreme wrist postures. By further shortening of handle length and/or limiting the angular deflection, joysticks can be designed that can be operated without extreme wrist postures, while the forearm is resting on an armrest. In this process, movement span of the joystick should be kept as large as possible and the optimal machine gain should be adjusted to this movement span. Even though the crane operators who took part in this study confirmed that task and crane unit felt very realistic, it seems advisable to test the joystick with the short handle in a field study on the specific machine in which it will be introduced. Besides joystick design, it can also be concluded from the present study that performance and physical load on the operator could be further optimized by adjusting gain settings to the task. It is recommended to optimize gain settings and joystick design simultaneously in relation to the task constraints observed in practice.

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